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# Recent Results from Fermilab E687

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**Abstract.** Recent analyses from Fermilab fixed target photoproduction experiment 687 [1] are summarized. Emphasis is placed on strong interaction studies performed on high statistics samples of Charm decays and light quark states. In particular, semi-leptonic measurements of form factors in Cabibbo suppressed modes are described. A Dalitz analysis of the $D_s^+ \to \pi^+\pi^-\pi^+$ has been performed and can be linked to recent results on scalar states decaying to $\pi^+\pi^-$. In addition, Charm-Anticharm asymmetries in high energy photoproduction have been measured. Finally, photoproduction of light quark states, such as the vector meson $\rho(1700)$ or the $f_0(980)$ are discussed.

## INTRODUCTION

Fermilab Experiment 687 took its first beam about a decade ago. The data I will be presenting were obtained during the 1990-1991 run. Reconstructed data have been available for quite sometime, and numerous results have been published [2]. In fact, very soon, the E687 data sample will be superseeded by the follow-on experiment FOCUS, which has on tape an order of magnitude more data taken with an upgraded spectrometer. Rather then presenting the exhaustive list of measurements made by E687 in this very productive decade, I'll concentrate on processes where the phenomenology of strong interactions matters. Too often "Charm physics" or "b-physics" are considered in isolation, as if Heavy quark physics is unrelated to other open questions in the Standard Model, such as light quark or exotic hadron spectroscopy. Although Charm physics allowed us to measure some fundamental parameters (CKM elements), it is likely that current or future measurements will become increasingly hard to interpret without confronting strong interaction physics, in the regime where QCD becomes non-perturbative. However, rather then considering this strong interaction as a nuisance, we should perhaps take the opportunity offered by the rich Heavy Quark weak decay phenomenology to study it more carefully. Finally, although E687 was designed as a Charm experiment, the spectrometer has unique features allowing us to make high sensitivity measurements in the light quark sector.

In E687, charm particles were produced by photons with average tagged energies of approximately 200 GeV colliding with a $\approx 4$ cm long Beryllium[1] target and detected by a wide-acceptance, multi-purpose spectrometer which is described in detail elsewhere [3]. Charged particle tracking and momentum analysis were accomplished by a high resolution silicon microstrip detector, five stations of multi-wire proportional chambers and two large magnets operated with opposite polarities. A system of three multicell Čerenkov detectors working in threshold mode provided charged hadron identification ($\pi^{\pm}, K^{\pm}, p^{\pm}$) over a large momentum range. Two electromagnetic calorimeters, both composed of alternating layers of lead and scintillators, were used to detect electrons in complementary regions of the spectrometer. The inner electromagnetic calorimeter covered the central solid angle around the beam direction and detected particles passing through the fields of the two magnets; the outer electromagnetic calorimeter covered the outer angular annulus described by particles passing through the field of the first magnet, but not the second magnet. Muons were identified only in the central region of the spectrometer by the inner muon detector, composed of three scintillator planes and four proportional tube planes; shielding was provided by the upstream detectors (mainly the inner electromagnetic and the hadron calorimeter) and two blocks of steel. The hadron calorimeter was primarily used in the trigger.

All the analysis in the Charm sector mentioned in this paper required at least two vertices, obtained either by the "candidate-driven" algorithm, valid for fully reconstructed final states, or by the "stand alone" method, where no apriori knowledge about the decay topology is assumed while forming vertices in the event. In order to obtain clean samples, in addition to conventional cuts such as those based on $\chi^2$ from track or vertex fits, numerous vertex cuts had to be considered. For instance:

- isolation cuts: leftover tracks not found in the primary vertex were required to be inconsistent with emerging from the secondary vertex, and secondary tracks were required not to point towards the primary vertex.
- Point back cut: For fully reconstructed decays, the charm particle direction can be reconstructed and must point back to the primary vertex.
- Requiring that the secondary vertex be outside the beryllium target allows us to reject background due to secondary interactions.

In addition, particle identification played a crucial role in these analyses. The efficiencies of the Čerenkov system in the presence of other tracks were care-

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1) a few % of the our data sample was obtained with a multi-layered target, consisting of lead, aluminum and Beryllium segments, in order to measure A-dependences

fully studied using $K_s^0 \to \pi^+\pi^-$, $\Lambda^0 \to p\pi^-$, $\phi(1020) \to K^+K^-$ decays and, most relevant, using the Cabbibo allowed decay of the $D^0$ meson from the $D^*(2010)$ decay selected by secondary vertex cuts.

In the light quark sector analysis, one and only vertex in the target is required. This cut was found to be very efficient on well reconstructed prompt events, and rejects most of the confused events where hadronic secondary interactions occured in the target. This allowed us to run the experiment at relatively high rates ($\approx$ 2,000 hadronic events per tevatron spill recorded), with a $\approx 10\%$ interaction length target, while the background due to reinteractions is as if we were running with a relatively thin target: $\sigma_Z \approx 500\mu m \approx 0.2\%$ interaction length. In addition, the forward hadron calorimeter, used in the trigger, has good acceptance for relatively high mass states produced diffractively.

# RESULTS

## Cabibbo suppressed, semileptonic decays of the D meson

As the Cabibbo allowed semileptonic decays are well established, experiments have begun turning their attention towards the more elusive Cabibbo suppressed, semileptonic decays ($D^0 \to \pi l\nu$ and $D^+ \to \rho l\nu$). These decays may be used to compare the functional dependence of form factors between Cabibbo favored and Cabibbo suppressed currents. In particular, E687 has observed the $D^0 \to \pi^- e^+\nu$ and $D^0 \to \pi^-\mu^+\nu$ (charge conjugate are always implied) [4]. Assuming the $D^0$ mass and using the direction of flight of the $D^0$ and the soft pion from the $D^{*+} \to D^0\pi^+$ decay, it is possible to fully reconstruct the decay kinematics, resolving correctly the $D^0$ momentum twofold ambiguity approximately 80% of the time, and extract a signal. We obtained:

$$\frac{BR\ (D^0 \to \pi^- l^+\nu_l)}{BR\ (D^0 \to K^- l^+\nu_l)} = 0.101 \pm 0.020(stat) \pm 0.003(syst)$$

Assuming a single pole mass dependence for the form factors, we determined:

$$\left|\frac{V_{cd}}{V_{cs}}\right|^2 \left|\frac{f_+^\pi(0)}{f_+^K(0)}\right|^2 = 0.050 \pm 0.011 \pm 0.002$$

Finally, untarity constraints on the CKM matrix set a value for the ratio $|\frac{V_{cd}}{V_{cs}}|^2$ and we can compute:

$$\left|\frac{f_+^\pi(0)}{f_+^K(0)}\right|^2 = 1.00 \pm 0.11 \pm 0.02,$$

consistent with expectation.

More recently, we observed the first statistically significant signal for the vector meson Cabibbo suppressed decay $D^+ \to \rho^0 \mu^+ \nu$ [5]. This decay had to be reconstructed without the help of the $D^*$ trick. However, three charged tracks are in this final state which greatly ease the vertex reconstruction. In addition, the lifetime of $D^+$ is relatively large. The background to the $M(\pi^-\pi^+)$ invariant mass distribution is adequately described by three sources: other $D^+$ and $D_s^+$ semileptonic decays involving two pions, semileptonic decays of the $D^0$ produced in $D^{*+}$ decays and charm hadronic decays. We measured the branching ratio of the decay mode $D^+ \to \rho^0 \mu^+ \nu$ (plus a possible unobserved $\gamma$ from $D^+ \to \eta' \mu^+ \nu$, $\eta' \to \gamma \rho^0$ ) with respect to the decay mode $D^+ \to \overline{K^{*0}} \mu^+ \nu$ to be

$$\frac{BR(D^+ \to \rho^0 \mu^+ \nu)}{BR(D^+ \to \overline{K^{*0}} \mu^+ \nu)} = 0.079 \pm 0.019 \pm 0.013$$

.

## Hadronic decays

Amplitude analysis of non-leptonic Cabibbo favored [6] and suppressed [7] decays have been previously studied by E687. These analyses have emerged as an excellent tool for studying hadron dynamics. In particular, the $D_s^+$ decay into three pions could be the best candidate to proceed through an annihilation diagram, since annihilation of the two initial quarks is Cabibbo favored and not suppressed as in the $D^+$ decay. However, a normal weak radiative decay of the type $c \to sW$, producing two kaons of opposite sign, followed by a rescattering $KK \leftrightarrow \pi\pi$, could also produce the same final state. This rescattering amplitude seems also to manifest itself through markedly different final states: the $f_0(980)$ meson appearing in the $D_s^+$ decay is absent in the $D^+$ decay [8]. The Dalitz plots for these two decays are shown in figure 1. Despite the limited statistics in the $D_s$ sample (less than about 100 events) a careful log-likelihood analysis of the final 5-amplitude fit demonstrates that we start to have some sensitivity to the $S(1475)$, consistent with the $f_0(1500)$, a broad scalar meson observed in $p\bar{p}$ annihilation and in the $J/\Psi$ decay [9]. Doubly and singly Cabibbo suppression has also been studied in the $K^+K^-K^+$ channel [10] and in the $K^+\pi^-\pi^+$ final state [11] The signal to noise ratio and the available statistics does not allow us to perform a meaningful Dalitz analysis. Hopefully, E831 with $\approx 10$ times more data should be able to improve our understanding of this phenomenology.

## Photoproduction of Open Charm

The photoproduction reaction in itself allows us to study hadron dynamics. Previous results validate the perturbative QCD inspired photon-gluon fusion model. Inclusive transverse and longitudinal momentum distributions of $D$ mesons were measured and found in good agreement with the Pythia/Lund Monte Carlo, which is based upon the photon-gluon model and hadronization via a string model [12]. However, the distributions of the correlation variables $\delta\phi$ and $P_t^2$ between the $D$ and the $\bar{D}$ meson were found to deviate substantially from this Lund Monte Carlo [13], probably due to hard gluon emission in the final state. Thus, it is likely that these variables are related to the details of the fragmentation process. New observations are required, such as the so-called Charm-Anticharm asymmetry. This asymmetry is defined as the normalized difference in yield between the charmed and anticharmed particle, for a given charm state (heavy-light meson or baryon). These asymmetries are expected to vary across the $x_f$ range. As our acceptance is limited at low or negative $x_f$, this acceptance correction for this inclusive Charm-Anticharm asymmetry[2] was found to be very hard to compute in a model independent way. Thus, we chose to report these measured asymmetries as such, and compare them to the Lund Monte Carlo [14]. We observed statistically significant asymmetries in the photoproduction of $D^+$, $D^{*+}$ and $D^0$ meson (with an average for all D meson of about $-3.7 \pm 0.6\%$) and find small (but statistically weak) asymmetries for the $D_s^+$ meson and the $\Lambda_c^+$ baryon. The kinematic dependence exhibited by our inclusive asymmetry measurements is qualitatively reproduced by the Lund model. However, the values are smaller in magnitude, which can be interpreted as an indication that the momentum fraction carried

[2] we typically observed only one Charmed (or AntiCharmed) hadron per event

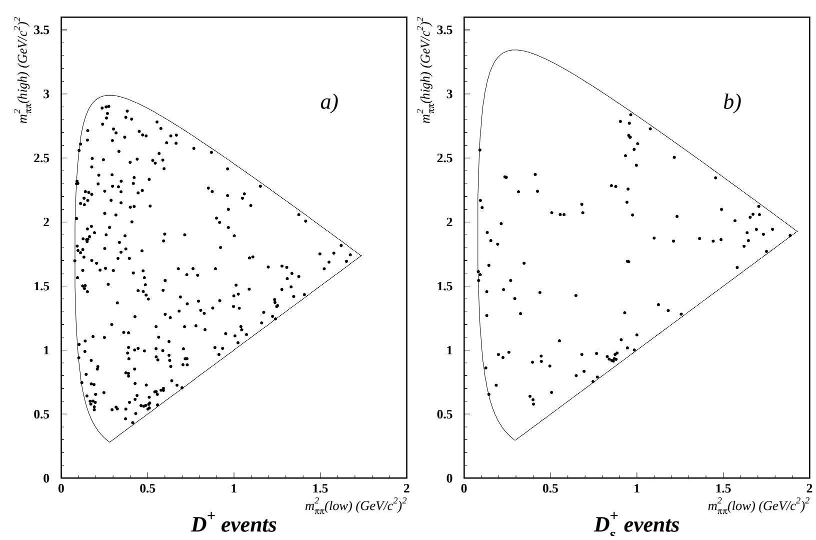


**FIGURE 1.** The $D^+$ (a) and $D_s^+$ (b) Dalitz plots for the $\pi^+\pi^-\pi^+$ channel, reconstructed using the “candidate-driven” method.

by the bachelor quark[3] is considerably harder than the Lund model predicts, using it's default paramters. This analysis is consistent with alternate LUND counting rules where the bachelor quark gets $\approx 2/3$ of nucleon momentum.

Such disagreements are not too surprising, as we are probably observing non-perturbative effects in the fragmentation process. Much remains to be done to resolve such complex dynamics: for instance, we know little about the relative photoproduction yields of excited Charmed mesons ($D^{**}$) states. Some of these states are thought to be very wide [15]. Therefore, these photoproduction dynamics must be studied in conjunction with detailed Charmed meson spectroscopy.

## Light quark sector

Let us now turn our attention to processes at even lower momentum transfer (where perturbative QCD definitely no longer works), and where spectroscopy and production dynamics are even more closely related. As mentioned above, E687 has good sensitivity for detecting light quark, diffractively produced states, decaying to charged hadrons. The Vector Dominance model works surprisingly well, even at these high energies: to first order, we are studying the vector mesons, in their fundamental or exited states. In particular, due it's relatively large coupling to to the photon, the $\rho(770)$ is ubiquitous. In addition, these vector states can be observed without interference with the target nucleon, due to the relatively large ($>\approx 3$) rapidity gap between these states and the nucleon. In other words, these are clean and simple reactions (Unfortunately the theoretical analysis in the context of QCD is far from obvious).

There is however one experimental limitation: the incident photon energy, measured in the tagging system [16] is not known with enough accuracy to verify that a given final state is exclusive. In most studies so far, we studied "quasi-exclusive" final states, that is, states where no other particles are observed in the spectrometer. In our kinematical regime, the Mandelstam variable $t$ is given by the transverse momentum. These $t$ distributions provide a consistency check on the exclusive, diffractive, character of the reaction, as their slopes are related to the size of the nucleus. This A-dependence of these $t$ slopes have been verified for the $\rho(770)$ and $\rho'(1600) \rightarrow \rho(770)\pi^+\pi^-$ channels.

The $\pi^+\pi^-$ invariant mass plots for the quasi-exclusive reaction $\gamma + Be \rightarrow Be + \pi^+\pi^-$ is shown in fig. 2, and has been corrected for acceptance. Only one $\rho'$ state is visible, at a pole mass of $1.66 \pm 0.010(stat)^{+.20}_{-.02}(syst.)$ GeV, the large systematic error being primarily due to model uncertainties in the

[3] In this model, the struck gluon leaves the target nucleon in a color octet state which can be divided into a color antitriplet pole, forming the "di-quark" and a color triplet pole, referred to as the "bachelor quark".

representation of the "background", non-resonant amplitude underneath the $\rho(770)$ [17,18]. Indeed, even at such high masses, the $\rho(770)$ and this accompanying "Drell-Söding" amplitude are as large as the excited $\rho$. A two-resonance model ($\rho(1450)$, $\rho(1700)$) works also, but does not improve the fit to the data, and introduces arbitrary phases. Within the context of the model, once the "Drell-Söding" is correctly taken into account the parameters of the $\rho(770)$ resonance observed in this experiment are consistent with those measured at $e^-e^+$ colliders, and a precise observation of the $\rho - \omega$ interference effect leads to a new estimation of the branching ratio $\omega(783) \rightarrow \pi^+\pi^-$equal to $1.95 \pm 0.02(stat) \pm 0.015(syst)\%$. (As the ratio of $\rho$, $\omega$ exclusive photoproduction ratio is not that well known at our energies, $SU(3)_{flavor}$ electromagnetic coupling [19] has been assumed.). As predicted, the relative phase between these two amplitudes is consistent with 90 degrees.

The excited $\rho$ meson(s) decay predominantly into 4 pions. In particular, the $2(\pi^+\pi^-)$ channel can be easily studied in our data set. The E687 spectrometer and the triggering system is very efficient for this all-charged, 4-prong final state, with an effective acceptance peaking around an invariant mass of about 1.7 to 2.0 GeV. The invariant mass plot shown in fig. 3 has been corrected for acceptance. Once again, it exhibits only one "bump", around 1.65 GeV.

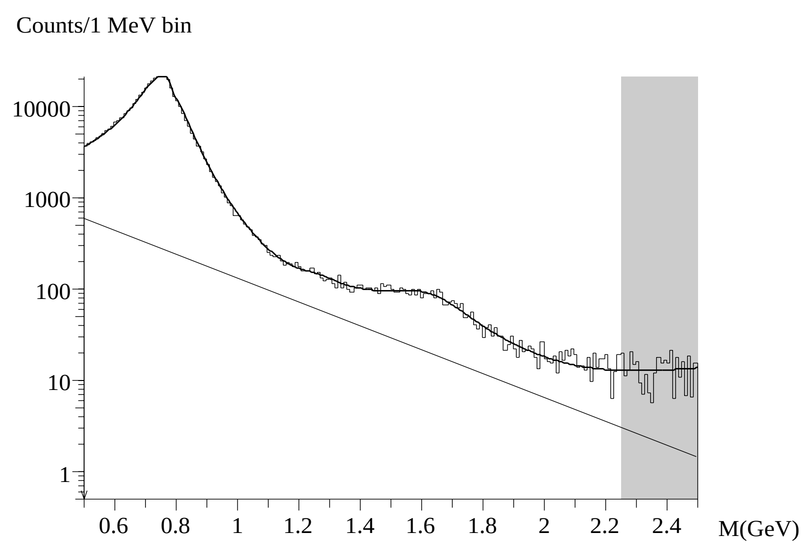


**FIGURE 2.** The quasi-exclusive $\pi^+\pi^-$ mass spectrum at low $t$ ($Pt^2 < 0.0625 GeV^{-2}$) , corrected for acceptance, showing the $\rho(770)$, the small but noticeable $\rho - \omega$ interference and the $\rho'(1700)$ signal. The fit is based on a model which includes these three vector states, the "Drell-Söding" non-resonant amplitude and an estimate of the non-interfering background, showing as the thin straight line on this log-plot. The fit does not include the shaded region.

The detailed analysis of the fit of this bump reveals that, obviously, this is not a simple resonance characterized by a single pole. A model based on three, strongly interfering Breit Wigner does not fit either. In addition, the "PDG" values for the pole masses of these $\rho'$ at 1.470 and 1.70 do not emerge from these fits. In order to understand this final state, it is necessary to carefully study the kinematics of this peculiar channel, where the same sign pions are completely in a Bose-Einstein symmetric final state. This reaction can either be understood as:

- The photoproduction of a leading $\rho(700)$ meson followed by a $\pi^+\pi^-$, S-Wave, with a small invariant mass $\approx 400$ MeV. If so, the peaking around 1,650 is driven by the masses and width of these two distinct substates and the Bose-Einstein symmetry of the $2(\pi^+)$, $2(\pi^-)$ state.
- The photoproduction of the $A_1(1320)$ meson decaying to $\rho(770)\pi$ and an additional pion.

Note also that a significant distortion of the $4\pi$ mass is observed at $\approx 2.1$ GeV, not predicted by either model.

Thus, reaction mechanisms and the spectroscopy of the light quark states, particularly with the possibility of including the $\sigma$ meson as a genuine state [20], are in fact intimately related.

Other interesting states have been observed in this experiment. For instance, in the $K^+K^-\pi^+\pi^-$ final state, it has been showed that the production

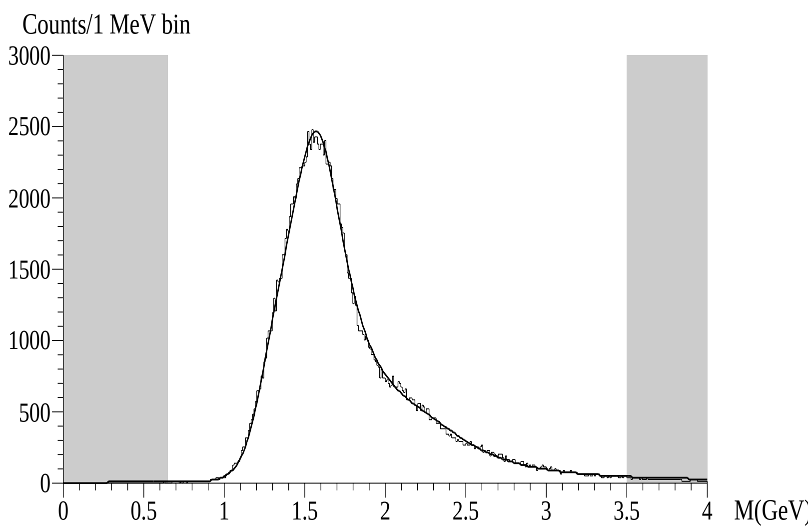


**FIGURE 3.** The quasi-exclusive $2(\pi^+\pi^-)$ mass spectrum, corrected for acceptance, showing the $\rho'(1700)$ "bump". The fit, which is not very good, is based on a model with three interfering Breit-Wigner resonance.

of the $f_0(980)$ meson is relatively enhanced if the $K^+K^-$ comes from a $\phi(1020)$ decay [21]. The photoproduction of the $\phi(1020)\phi(1020)$ system has also been observed and we studied the $f_1(1285)\pi$ final state, searching for an exotic $1^{+-}$ state around 1.75 GeV. We hope that these studies will resume once the data from the follow-on experiment, E831 will become available.

## CONCLUSION

It is becoming increasingly evident that the current investigations of Charm physics, hadronic decays in particular, offer much insight into the Strong Interaction. Although more precise determinations of the CKM matrix elements remains an important task, we will have very large Charm samples in the near future (we expect $\approx 1,000,000$ fully reconstructed charm decays from E831), allowing precise measurements of a large number of decay amplitudes. Rather than considering the details of the Strong Interaction a nuisance, we should take this opportunity to study this interaction. Finally, these Charm spectrometers are actually quite well suited to study the light quark vector mesons and their excited states.

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